WORKING PAPER SERIES
ISSN 1973-0831

WORKING PAPER
N. 98
SEPTEMBER 2017

TO WHAT EXTENT WILL CLIMATE AND LAND-USE CHANGE AFFECT EU-28 AGRICULTURE?

A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

Martina Sartori, Davide Geneletti, Stefano Schiavo and Rocco Scolozzi

Università Bocconi
IEFE
Centre for Research on Energy and Environmental Economics and Policy

To what extent will climate and land-use change affect EU-28 agriculture? A computable general equilibrium analysis

Martina Sartori[a*] Davide Geneletti[b] Stefano Schiavo[c] Rocco Scolozzi[b]

September 2017

Abstract

This paper assesses the structural, joint implications of climate and land-use change on agriculture in the European Union, by means of a computable general equilibrium model of the world economy. The counterfactual simulations are conducted at the year 2050 under the second Shared Socioeconomic Pathway.

We find that climate and land-use change are likely to affect agricultural systems very differently across Europe. Northern countries are expected to benefit from climate change impacts, whereas other areas in Europe will suffer negative consequences in terms of reduced agricultural output, real income and welfare. The most vulnerable region is not made of Mediterranean countries, but rather Central Europe. Our results suggest that climate and land-use changes may exacerbate existing disparities within the EU. Therefore, appropriate adaptation strategies and a more flexible land-use are required to limit these negative consequences and possibly exploit the beneficial effects of climate change in some countries.

Keywords: agricultural productivity shock, climate change, land-use change, general equilibrium analysis.

JEL classification: C68, Q11.

Acknowledgements

Financial support received through the projects ''CLIMatic change impacts on future Availability of WAter REsources and hydro-geological risks - CLIMAWARE" funded by the University of Trento; and "Sustainable Integrated Management for the Nexus of Water-Food-Land-Energy-Climate for a Resource Efficient Europe – SIM4NEXUS" funded by European Commission (H2020-WATER-2014/2015 funding scheme) is gratefully acknowledged.

[a] IEFE – Bocconi University.

[b] University of Trento – Department of Civil, Environmental and Mechanical Engineering.

[c] University of Trento – Department of Economics and Management and School of International Studies.

*Corresponding author: martina.sartori@unibocconi.it

1. Introduction

Despite its relatively small geographical extension, the European Union -EU- is one of the world's largest producers of agricultural products (FAO, 2007). According to EUROSTAT (2015)[1], total agricultural production in 2014 amounted to around 1122.4 million tons, about 10% of world total production. Thanks to its varied climatic and topographic conditions, the EU produces a broad range of crops, fruits and vegetables. The harvested production of cereals (including rice) is estimated to be around 334.2 million tons in 2014, about 13% of global cereal production. Sugar beet accounts for around 50% of the global production, while two third and three quarters of wine and olive oil produced globally come from the EU.

Agriculture is one of the human activities most dependent on climate, and unfortunately climate change is expected to affect dramatically this sector (IPCC, 2014). Bindi and Olesen (2011) find that the effects of climate change -and increased atmospheric CO_2- are expected to slow down European crop productivity growth, despite technological development (e.g. new crop varieties and better cropping practices) might outweigh the effects of climate change (Ewert et al., 2005). Recently, cereal grain yields have flattened out, indicating that climate change may play a greater role than technological progress (Kristensen et al., 2010).

The extent and magnitude of the impacts are, however, uncertain, given the great deal of complexity in the climate-land-food systems. According to Alcamo et al. (2007), the consequences of climate change on agricultural ecosystems are likely to vary widely depending on the cropping system (i.e. cereals vs. forage crops vs. perennial horticulture), the hydrological features, water uses and management approaches of each region. The actual effect depends on several factors, which are either country-specific (e.g., the geography, soil type, water conditions and existing forms of food production) or difficult to evaluate ex-ante. Variations in regional temperature, different regional patterns of precipitations, the amount of fertilization due to higher CO_2 concentration, the actual level of water available for irrigation, irrigation techniques, adaptation strategies including variety selection, crop rotation and sowing times are all factors potentially modifying crop yields and thus agricultural productivity. In addition, local demography and local economy act as exogenous drivers in combination with EU common agricultural policy (CAP), aiming at improving agricultural productivity to ensure that EU farmers can make a reasonable living.[2] Where the population is declining and the economy stagnating, the subsidies from CAP may effectively increase the land dedicated to farming.

Climate change also affects the total amount of land available for agricultural purposes through different drivers. First, rapid and extreme events, like floods, are opposed to long-term climate induced events, which have long duration (from months to years) and slow onset. In the latter case, the effect on land-use can hardly be reversed (IPCC, 2014). Second, climate change is expected to affect the

[1] http://ec.europa.eu/eurostat/data/database.

[2] https://bookshop.europa.eu/en/agriculture-pbNA0216625/

distribution of vegetation and, consequently, land cover types: elevation and latitude of the land will have higher influence on crop distribution (Gobiet et al., 2014). In addition, changes in biodiversity due to climate change are expected to increase the vulnerability of regional agriculture, for instance in terms of higher sensitivity to pests, and consequently the likelihood of land abandonment in some regions (Rounsevell et al., 2006). The economic strength of farms, the pressure on agriculture land by other land uses or social drivers (e.g. migration) may challenge the adaptive capacity of regional systems (Hermans et al., 2010; Greiving, 2011), resulting in the fact that the long-term future development of European agriculture will depend on the local combination of the mentioned factors.

Most existing research focuses on the likely direct impacts on crop yields and agricultural output of climate change only (e.g., Jones and Thornton, 2003; Hertel et al., 2010; Ciscar et al., 2011; Lavalle et al., 2010). Most of them focus on other world regions, especially the USA (Schlenker et al., 2005; Deschênes and Greenstone, 2007) and the Mediterranean region (García-Ruiz et al., 2011; Iglesias et al., 2011; Roson and Sartori, 2015), or are limited to a single or a group of European countries, relying on econometric techniques (Lang, 2007; van Passel et al., 2016).

In this paper we simulate the structural joint consequences of both climate and land-use change on agriculture[3] in the EU, at the year 2050. A first novelty of this study is the combination of different modeling frameworks, each delivering key inputs for and output of the analysis. The analysis of climate change impact on agriculture follows Roson and Sartori (2016) and models climate change as a shock to agricultural productivity. Then, the Land-Use-based Integrated Sustainability Assessment -LUISA- Territorial Modeling platform (Baranzelli et al., 2014) provides the estimates on land-use changes. Finally, the two inputs are fed to a computable general equilibrium (CGE) model of the world economy to gauge the overall impact of climate change (through variations in agricultural productivity) and land-use change on the agriculture sector of the European Union. The CGE model database is disaggregated into the 28 EU Member States and two residual regions (rest of Europe, rest of the world). The economy of each EU Member State is "perturbed" with the estimated variations in agricultural productivity and land-use change. A second novelty of this study is that the counterfactual simulations are conducted on a 2050 baseline, where the economic structure of the EU28 is consistent with the population and Gross Domestic Product (GDP) levels projected under the "Middle of the Road" Shared Socioeconomic Pathway, SSP2 (Kriegler et al., 2012; KC and Lutz, 2014; O'Neill et al., 2017).[4]

The paper is structured as follows. The next Sub-section describes the modeling approach. Section 2 is devoted to the description of the methodology applied to estimate the climate change and land-use change impacts on agriculture. Section 3

---

[3] Livestock production is excluded from this analysis.

[4] SSPs include a storyline or *narrative*, which describes plausible alternative changes in aspects of society such as demographic, economic, technological, social, governance and environmental factors.

illustrates the results obtained from the economic analysis, while Section 4 reports the results of the sensitivity analysis conducted on climate change impacts. Finally, Section 5 provides some conclusions.

1.1 Modeling strategies and the general equilibrium analysis

The macroeconomic consequences of reduced land availability and lower productivity of agriculture go far beyond a drop in agricultural production (yields). In fact, lower output brings about an increase in the price of domestic products, which become relatively more expensive than foreign products. This change in relative prices may cause the substitution of some domestically produced agricultural goods with imports in both production and consumption processes, triggering a devaluation of the national currency (necessary to ensure a trade balance) and a change in the whole structure of the economic system. Vice-versa, larger availability of land and increased productivity generate opposite effects.

To account for the multiple system-wide economic consequences, a Computable General Equilibrium (CGE) model is the appropriate tool (see e.g. Dixon and Jorgenson, 2013). A CGE model is a large non-linear system that provides a systemic and disaggregated representation of national, regional and multi-regional economies. It fully accounts for circular income flows, inter-sectoral and market linkages, changes in relative competitiveness. The economy is treated as an integrated system, in which markets influence each other, resource are constrained, prices are allowed to vary and demand and supply must balance under behavioral assumptions of Walrasian perfectly competitive market. Model parameters are calibrated using real world data from Social Accounting Matrices (SAM), whereas counterfactual simulations are obtained by changing exogenous variables and parameters. The counterfactual equilibrium computed for the global economy is compared to the benchmark/baseline equilibrium, where no shock perturbed the economy. A major advantage of using a general equilibrium model is that industry prices of *all* possible markets (not only agricultural markets) are endogenous, so that the loss of productivity occurring in agriculture is partly compensated by an increase in the relative price of agricultural products, thus enhancing the value of the reduced output.

The model used in this exercise is the CGE model of the Global Trade Analysis Project (GTAP), whose mathematical structure is fully described in Corong et al. (2017) (see the Appendix for more details). The model is calibrated on version 9 of the GTAP Data Base (Aguiar et al., 2016), at the year 2011. The database is disaggregated into the 28 EU Member States[5] and two residual regions, Rest of Europe and Rest of the World.

[5] Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and UK.

Figure 1 summarizes the methodology followed to simulate the consequences of both climate and land availability change on agriculture. The counterfactual simulations are conducted at the year 2050, under the second Shared Socioeconomic Pathway, SSP2, termed the "Middle of the Road" scenario. SSP2 is a pathway characterized by a modest overall growth in population and incomes, and a slow pace of overall trade liberalization. Data on projected population and income levels by country are used to obtain a plausible baseline of the whole economy at the year 2050. Percentage changes of GDP and population reported in Table A1 of the Appendix are applied to the corresponding variable in the CGE model, so that the model generates a counterfactual baseline scenario, where the value of the other macroeconomic variables is consistent with the projected population and GDP. The 2050 SSP2 baseline is then "perturbed" to account for the climate change impact on agricultural productivity and the variations in land available for agriculture – land-use change. In particular, (i) the productivity of agricultural crops is varied by the percentage changes reported in Table 2 of Section 2.1, as a result of climate change; and (ii) agricultural land is scaled up or down according to percentages shown in Table 3 of Section 2.2.

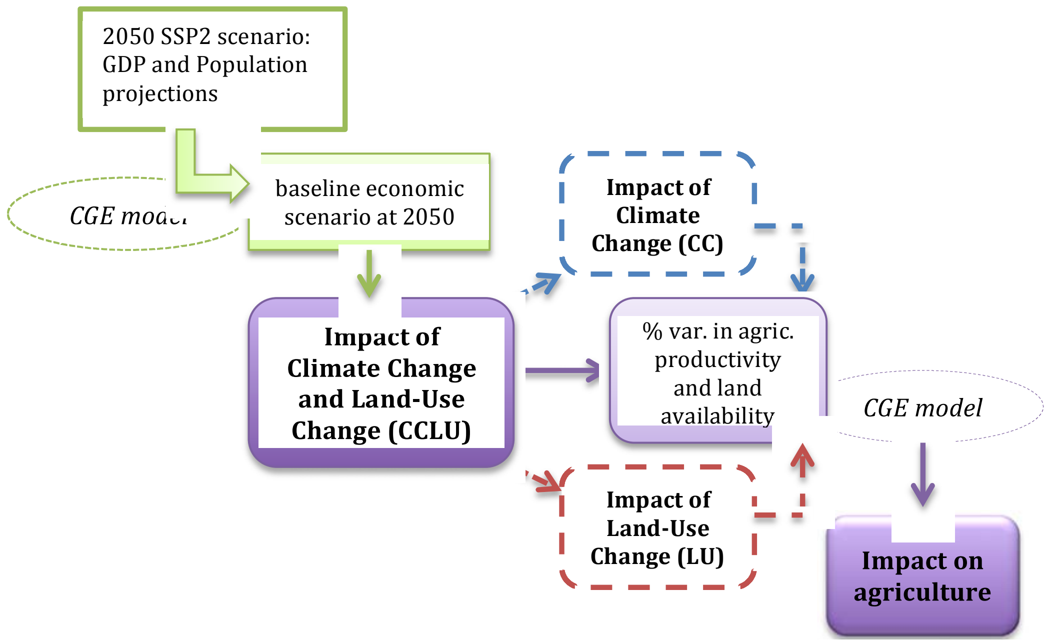


Figure 1. Methodological approach followed in this study.

2. The impact of climate and land-use change on the European agriculture

2.1 Climate change impact on agricultural productivity

The impact of climate change on agricultural productivity is estimated by applying the methodology proposed by Roson and Sartori (2016). In their contribution, the authors define a set of climate change impact functions, relating physical impacts of climate change (typically variations in average temperature, precipitation levels and

CO_2 concentration) to economic impacts in various dimensions, for a set of countries, including all European economies. When it comes to estimate the impact on crop yield, two damage functions are defined. One function estimates sectoral productivity variations in the yields of rice, wheat and maize only, and is obtained on the base of meta-analyses provided by the IPCC (2014); a second function estimates productivity changes of the aggregated agricultural sector, elaborating on Cline (2007). In both cases, crop yield is expressed as a function of local mean temperatures.[6] As the disaggregation of the dataset used in this study allows to keep "Rice", "Wheat" and the broader category "Cereals" disaggregated, the first crop-specific impact function is applied to these three categories, whereas the second impact function is applied to an aggregated residual category "Other Crops".[7]
Predicted local average temperatures at the year 2050 are retrieved from the GAEZ dataset and are shown in Table 1. In the EU, temperatures are expected to rise by +1.75°C, on average (IPCC, 2014). The largest increases will likely be registered in Northern-Eastern countries (e.g., Finland, Estonia, Hungary, Sweden, Latvia, Lithuania), whereas among the smallest increases there are some Mediterranean and central Europe countries (e.g., Greece, Cyprus, Austria, Luxembourg and the UK).[8]

Table 1. Predicted average temperature (°C) and standard deviation at the year 2050

	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
Countries	*Temp. 2011*	*Avg temp. 2050*	*Stand. Dev.*	*Variation*	*Countries*	*Temp. 2011*	*Avg. temp. 2050*	*Stand. Dev.*	*Variation*
Austria	7.89	8.52	2.96	0.63	**Italy**	13.4	14.47	4.00	1.07
Belgium	10.18	11.19	0.67	1.01	**Latvia**	5.67	8.16	0.58	2.49
Bulgaria	12.23	13.40	2.03	1.17	**Lithuania**	6.6	8.68	0.29	2.08
Croatia	11.43	13.36	2.17	1.93	**Luxemb.**	9.76	10.68	0.49	0.92
Cyprus	19.18	20.03	1.26	0.85	**Malta**	18.85	20.19	0.21	1.34
CzRep.	8.2	9.65	1.04	1.45	**Netherl.**	10.03	11.05	0.39	1.02
Denmark	8.11	9.60	0.35	1.49	**Poland**	8.38	10.06	0.69	1.68
Estonia	4.66	7.54	0.49	2.88	**Portugal**	15.53	17.32	1.92	1.79
Finland	0.01	3.86	2.11	3.85	**Romania**	10.25	12.08	2.21	1.83
France	11.26	12.50	2.16	1.24	**Slovakia**	8.88	10.41	1.81	1.53
Germany	8.76	10.41	0.81	1.65	**Slovenia**	9.61	11.17	1.90	1.56
Greece	15.59	16.26	2.50	0.67	**Spain**	14	15.46	2.89	1.46
Hungary	10.28	13.09	0.65	2.81	**Sweden**	1.75	4.33	3.20	2.58
Ireland	10.02	10.02	0.63	0.00	**UK**	9.22	9.59	1.42	0.37

Source: GAEZ database

[6] For a detailed description of how the damage functions are obtained, the reader may refer to Roson and Sartori (2016), Section 4.

[7] Maize is a cereal, so we applied the resulted productivity change of maize to the whole category "Cereals". The residual agricultural sector "Other Crops" contains oilseeds, fruits and vegetables, plant-based fibres and nuts.

[8] The GAEZ database (http://www.fao.org/nr/gaez/about-data-portal/agro-climatic-resources/en/) collects projections on several climate variables, including average temperature, obtained from a number of General Circulation Models (e.g., Hadley CM3, MPI ECHAM4, CSIRO Mk2, etc.) on the base of some SRES climate scenarios (A1F, A1, A2, B1 and B2), developed for the IPCC Fourth Assessment Report. As the mean value of the models projections are very similar across SRES scenario, results of this study has been produced by using mean temperature projections generated by the Hadley CM3 model, B2 SRES scenario, for the year 2050.

By applying the percentage variations in average temperature shown in Table 1 to the damage functions provided by Roson and Sartori (2016), estimates of productivity changes in "Rice", "Wheat", "Cereals" and "Other Crops" are obtained and shown in Table 2. The variations in average temperature affects European agricultural productivity differently, depending on (i) the climate zone where countries are located, and (ii) the crop response to changing local temperatures, which is generally not linear and fully taken into account in the climate change damage functions (Mendelsohn and Schlesinger, 1999; Schlenker and Roberts, 2009; Lobell and Burke, 2010).

Table 2. Impact of climate change on agricultural productivity by crop category and weighted net impact on total productivity.

Countries	*Rice*	*Wheat*	*Cereals*	*Other Crops*	*Weighted impact*
Austria	-4.8%	-6.8%	-0.2%	0.3%	-0.44%
Belgium	-5.1%	-7.4%	-0.2%	0.2%	-0.26%
Bulgaria	-4.3%	-5.6%	-0.8%	-0.2%	-1.38%
Croatia	-3.1%	-6.2%	-2.4%	1.0%	-0.88%
Cyprus	-3.5%	-3.9%	-1.4%	-1.4%	-1.55%
CzRep.	-4.1%	-6.9%	-1.0%	0.5%	-1.12%
Denmark	-4.5%	-7.8%	-0.4%	0.6%	-1.05%
Estonia	-1.1%	-0.8%	-1.2%	1.8%	0.96%
Finland	-7.6%	8.3%	-3.9%	4.0%	2.55%
France	-4.7%	-6.5%	-0.5%	0.1%	-1.45%
Germany	-4.2%	-7.0%	-0.9%	0.5%	-0.85%
Greece	-3.9%	-4.0%	-0.6%	-0.7%	-0.95%
Hungary	-1.6%	-4.6%	-2.9%	0.3%	-1.22%
Ireland	-5.3%	-7.9%	0.0%	0.0%	-0.61%
Italy	-4.2%	-5.3%	-0.9%	-0.8%	-1.24%
Latvia	-3.4%	-6.8%	-0.9%	1.4%	-0.84%
Lithuania	-3.4%	-6.8%	-1.1%	1.0%	-0.44%
Luxemb.	-5.0%	-7.1%	-0.3%	0.2%	-0.17%
Malta	-3.2%	-4.9%	-2.5%	-2.2%	-2.25%
Netherl.	-5.3%	-7.8%	-0.1%	0.2%	0.04%
Poland	-4.3%	-7.2%	-0.8%	0.6%	-0.45%
Portugal	-3.0%	-6.0%	-3.1%	-2.5%	-2.57%
Romania	-3.2%	-6.3%	-2.3%	0.3%	-0.51%
Slovakia	-4.1%	-6.7%	-1.1%	0.5%	-0.70%
Slovenia	-3.9%	-6.3%	-1.4%	0.4%	-0.12%
Spain	-3.5%	-5.5%	-2.0%	-1.4%	-1.64%
Sweden	-2.2%	-3.5%	-0.5%	2.5%	1.46%
UK	-5.6%	-9.3%	0.1%	0.1%	-1.85%

Wheat is the most affected crop, with a predicted average decrease of -6.5%, followed by rice (-3.9%) and cereals (-1.2%). Finland and the UK are expected to experience a positive impact on the agricultural productivity of wheat and cereals, respectively. The impact on the residual sector "other crops" is negative for all the countries located in South Europe, whereas for the remaining countries the impact is positive (0.3% on average). This different outcome may be explained by either the differences between the two types of damage functions employed to compute the changes in productivity or the composition of the residual aggregate of agricultural good, which is very heterogeneous, with possible opposite-sign impacts averaging out.

The overall impact of climate change on the productivity of the whole agricultural sector is not uniform across Europe. In some countries, especially those located at higher latitude, warmer average temperatures turn out to be beneficial to the agricultural productivity of some crops, in particular to the residual crops category, and the whole impact is positive. Higher average temperature in this climatic zone increases growing potential and extends growing season. The net impact turns out to be more severe in Southern Europe (Portugal, Malta, Spain), but also in the UK, France, Bulgaria and Hungary are significantly affected. Yet, these national-level estimates may hide some local and sub-national variability, due to different internal climate conditions. All in all, despite the significant reductions expected in the productivity of rice, wheat and cereals, the net impact on the whole sector is smaller, as the share of these three crop categories over the total agricultural production is minor (see Table A1 in the Appendix).

2.2 *Land-use change and its effects on agriculture*

Land-use change affects agriculture in the sense that more or less land will be available for crop cultivation. Estimates on land-use change were retrieved from the LUISA Territorial Modeling platform, built by the Joint Research Centre of the European Commission (LUISA - Land-Use-based Integrated Sustainability Assessment, Baranzelli et al., 2014). These estimates are not available by crop, but only in terms of generic "agriculture" land-use class. Therefore, the estimated variations in agricultural land endowments reported in Table 3 are applied uniformly to each crop category.

The LUISA platform integrates a suite of models, considering the demand and supply of resources and socio-economic activities and infrastructures, and merges both top-down and bottom-up dynamics to simulate land-use changes (Baranzelli et al., 2014). Scenarios consist of land-use allocation in space and time considering macro drivers as simulated by sectoral models (such as RHOMOLO, GEM-E3, CAPRI, POLES, etc.), through different geo-spatial models (such as TRANSTOOL, LISFLOOD, Regional Climate Models, BIOMA, etc.). The latter models provide thematic physical and geographical layers, while overall long-term demographic (trends and migrations) and economic projections are retrieved from Eurostat and ECFIN (for further detail on the modeling, see EC, 2016). In practice, the "demand" module of LUISA is a set of procedures that capture macro drivers of land-use change (taken from a set of upstream models) and transform them into actual regional quantities of the modeled land-use types.

Specifically, in LUISA, "land demand" is specified for four main groups of land-use classes: urban, industry-commerce, agriculture and forest. The 'agriculture' land-use class includes various types of land used to produce food, feed and fiber, thus comprising arable and pasture land, and permanent crops. Regional land demands for agricultural commodities are taken from the CAPRI model (Britz and Witzke, 2008), which simulates market dynamics using nonlinear regional programming techniques to forecast the consequences of the Common Agricultural Policy. This ensures consistency between the CAP-compliant economic and market assumptions, and the physical space occupied by the commodities grown in each simulated region.

At the year 2050, agricultural land is likely to decrease in the majority of the countries, with the largest absolute reductions occurring in France, Germany, Poland, the UK and Italy, which are also among the largest producers of agricultural goods in Europe (see Table A1 in the Appendix). A larger availability of agricultural land is predicted for some North-Eastern countries, so a shift of agricultural production toward this region is expected to occur, due to climate change.[9] Surprisingly, an increase in the amount of agricultural land is predicted for some Southern economies as well, such as Cyprus, Greece, Portugal and Spain. Such increase could be explained by considering the recent dynamics in these countries, causing synergistic effects that might promote the extensive agriculture, then the agriculture land. In words: a stable or decreasing demography decreases the demand for urban areas, a stagnating economy halts the demand for productive lands, the CAP subsidizes the extensive crops; these three processes seem to simultaneously occur especially in the mentioned areas.

Table 3. Agricultural land in 2010 and projected changes for 2015 (km^2).

	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
Countries	***2010***	***2050***	*Diff.*	*% Var.*	*Countries*	***2010***	***2050***	*Diff.*	*% Var.*
Austria	31,286	27,349	-3,937	-12.6%	**Italy**	160,529	151,954	-8,575	-5.3%
Belgium	18,547	15,507	-3,040	-16.4%	**Latvia**	21,164	24,203	3,039	14.4%
Bulgaria	59,601	57,817	-1,784	-3.0%	**Lithuania**	38,267	35,871	-2,396	-6.3%
Croatia	20,228	20,222	-6	-0.0%	**Luxemb.**	1,458	1,051	-407	-27.9%
Cyprus	4,696	4,883	187	4.0%	**Malta**	179	163	-16	-8.9%
CzRep.	46,681	43,556	-3,125	-6.7%	**Netherl.**	23,616	22,029	-1,587	-6.7%
Denmark	31,898	30,974	-924	-2.9%	**Poland**	201,092	161,428	-39,664	-19.7%
Estonia	12,894	14,479	1,585	12.3%	**Portugal**	35,395	35,676	281	0.8%
Finland	8,783	18,627	9,844	112.1%	**Romania**	149,458	139,781	-9,677	-6.5%
France	344,444	317,767	-26,677	-7.7%	**Slovakia**	24,391	23,044	-1,347	-5.5%
Germany	209,040	185,860	-23,180	-11.1%	**Slovenia**	6,690	6,216	-474	-7.1%
Greece	61,938	64,219	2,281	3.7%	**Spain**	263,391	265,845	2,454	0.9%
Hungary	63,599	58,829	-4,770	-7.5%	**Sweden**	19,742	37,303	17,561	89.0%
Ireland	47,330	46,209	-1,121	-2.4%	**UK**	139,480	128,593	-10,887	-7.8%

Source: Own elaboration using the datasets produced by the LUISA platform

Estimates reported in Table 2 and 3 are summarized graphically in Figure 2.

[9] A relatively large area of land will become increasingly available and attractive to agriculture and forestry. For example, in the northern Scandinavian countries (Norway, Sweden and Finland), it is expected that the boreal region will shift some 600 km further North (IPCC, 2014).

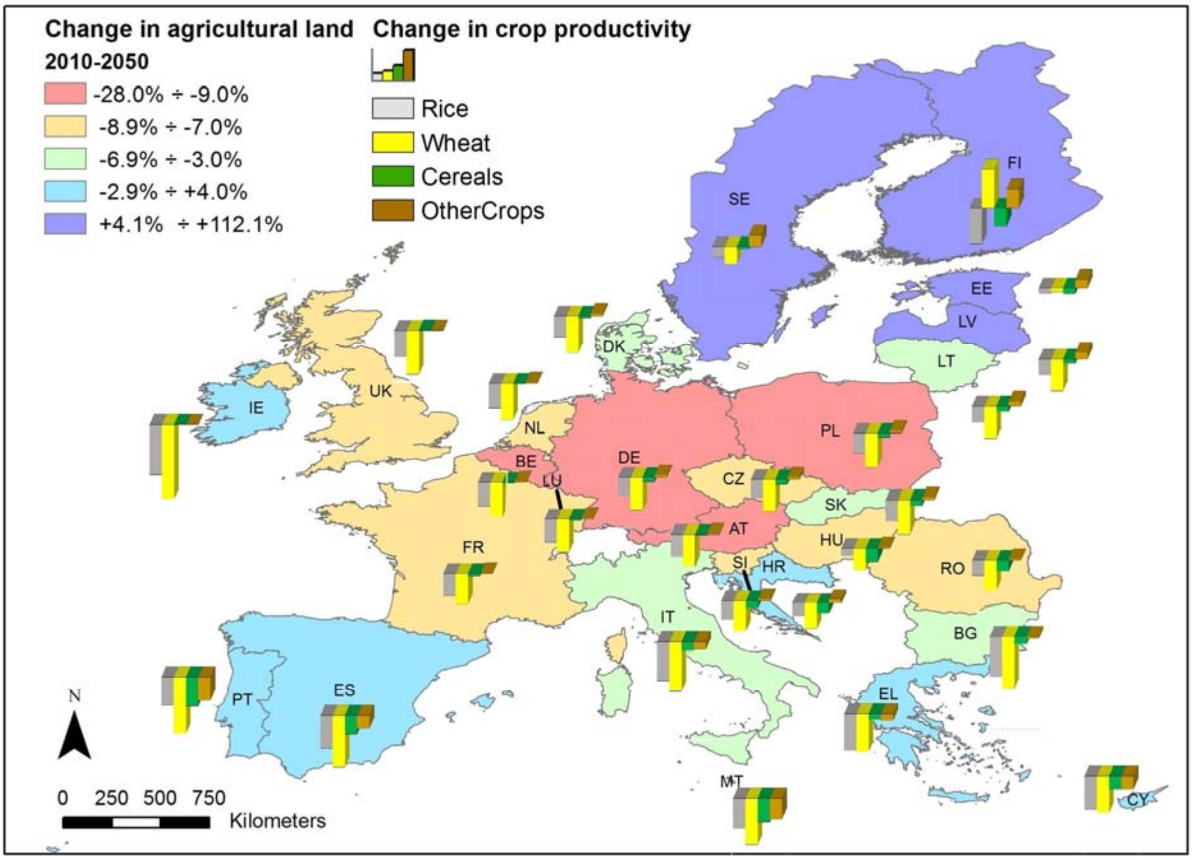
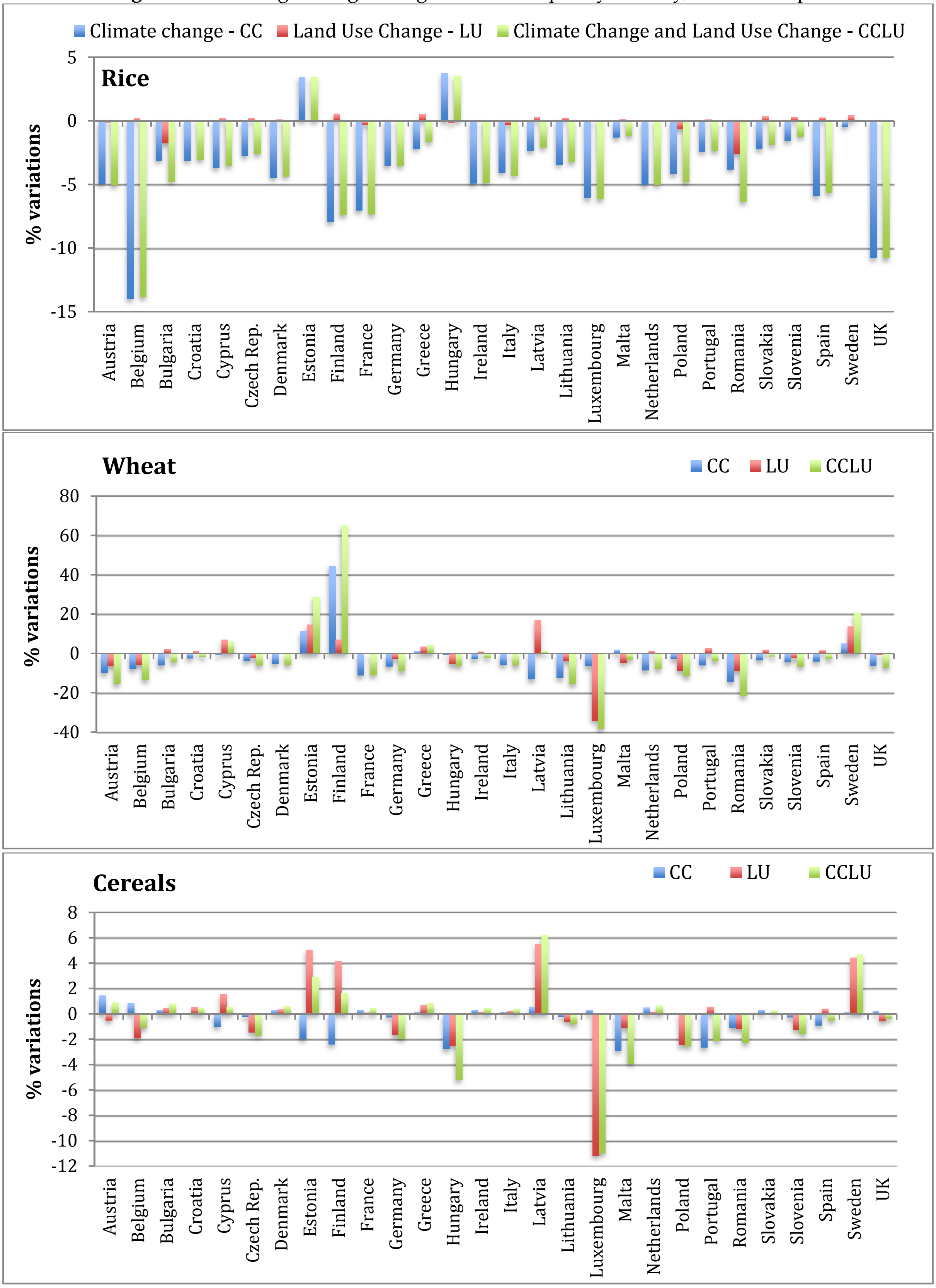


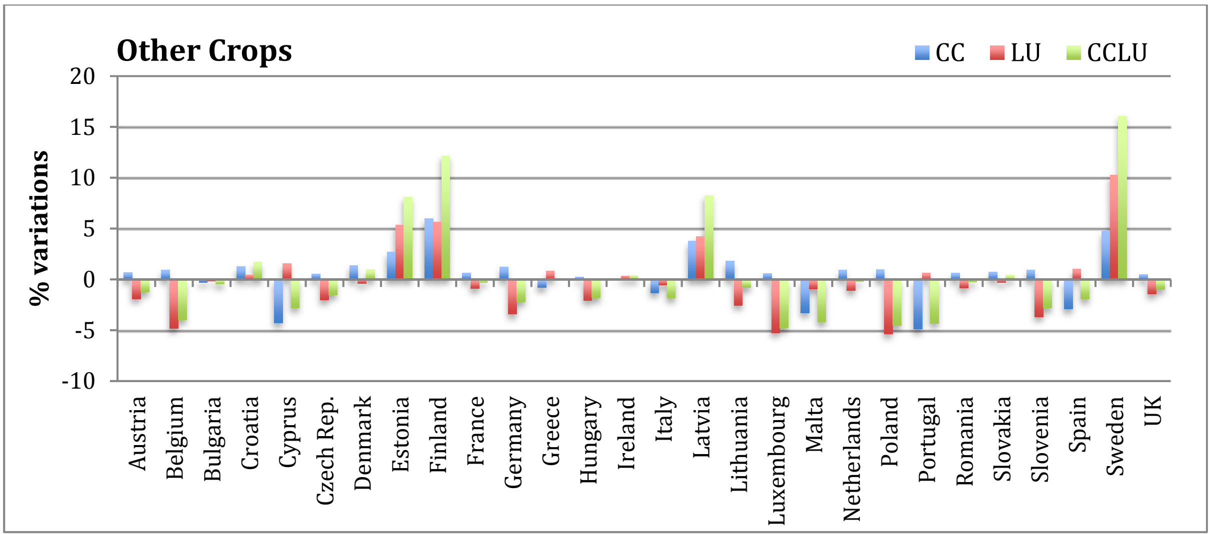
Figure 2. Changes in agricultural land and crop productivity by EU country at the year 2050.

2.3 Macroeconomic results

Figure 3 illustrates the percentage variations in total yield by crop category. The impact on agricultural output varies substantial both across countries and crops. Not surprisingly, the impact on agriculture is negative for the countries suffering from loss in land endowment and productivity, and vice versa. However, variations in industrial output are different from changes in productivity, as expected, because the change in relative competitiveness among sectors is fully accounted for in the general equilibrium model. More specifically, when productivity drops, production volumes fall not only because lower output is obtained with the same factors, but also because higher costs in that sector bring about lower demand. A general equilibrium economic analysis enables us to appreciate such a secondary order effects.

Figure 3. Percentage changes in agricultural output by country, various crops.





Depending on the crop type and country, the overall impact on crop yield may vary substantially. For example, wheat production is expected to drop by -38.55% in Luxemburg, driven by land-use change, and to rise dramatically by 65.36% in Finland, due to climate change.

The overall impact on rice production is negative for all countries, although rice production in Europe is relatively low so that the impact is set to be minor, with the exceptions of Hungary (3.53%) and Estonia (3.40%), mostly driven by climate change; rice productions in Belgium and the UK are the most negatively affected, with a projected decrease of -13.84% and -10.78% respectively.

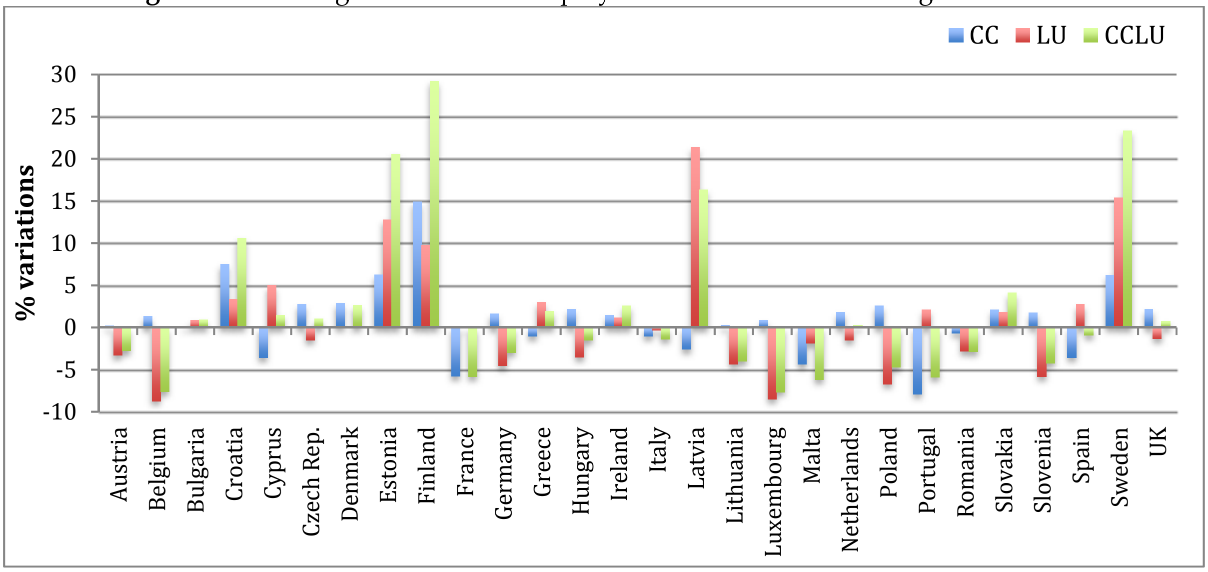
The expected variations in the yield of the various crop categories (with the exception of rice) are qualitatively similar within the same country. For example, agricultural production in Sweden, Finland and Estonia is expected to grow, regardless the crop type under consideration. The reverse holds true for e.g. Hungary, Germany, Spain, Slovenia, the UK and Belgium. For other countries, like Italy, France and Cyprus, changes in crop production are positive for some product categories and negative for others.

Consistently with the literature, climate-related increases in crop yields are expected above all in northern European countries (e.g., Alexandrov et al., 2002; Ewert et al., 2005; Audsley et al., 2006; Olesen et al., 2007; Richter and Semenov, 2005). Unlike other studies, this analysis reveals that among the countries expected to suffer the largest reductions in wheat and cereals yields there are non-Mediterranean countries, like Germany, Poland, Hungary, Belgium and Luxembourg. The negative impact is often driven by changes in land-use, neglected in other studies but extremely important to gauge the overall impact on national crop production. These countries are expected indeed to suffer the largest percentage reductions in land available for agriculture (see Table 3).

Clearly, variations in the agricultural output do affect employment level in the same sector. Figure 4 illustrates the overall impact expected on the employment of the agricultural sector. Changes in employment levels reflect the expected percentage variations in crop yields illustrated in Figure 3. A higher agricultural productivity and a larger availability of land bring about an expansion of the whole agricultural sector, which demands additional workers. This is the case of many northern-European countries (e.g., Finland, Sweden, Estonia and Latvia), where the increase in agricultural output pushes up the demand for labor (in agriculture) by 15 to almost 30%. In fact, these increases are not so substantial as they might appear at a first glance, given the small share of labor employed in agriculture in these countries (see Table A3 in the Appendix).

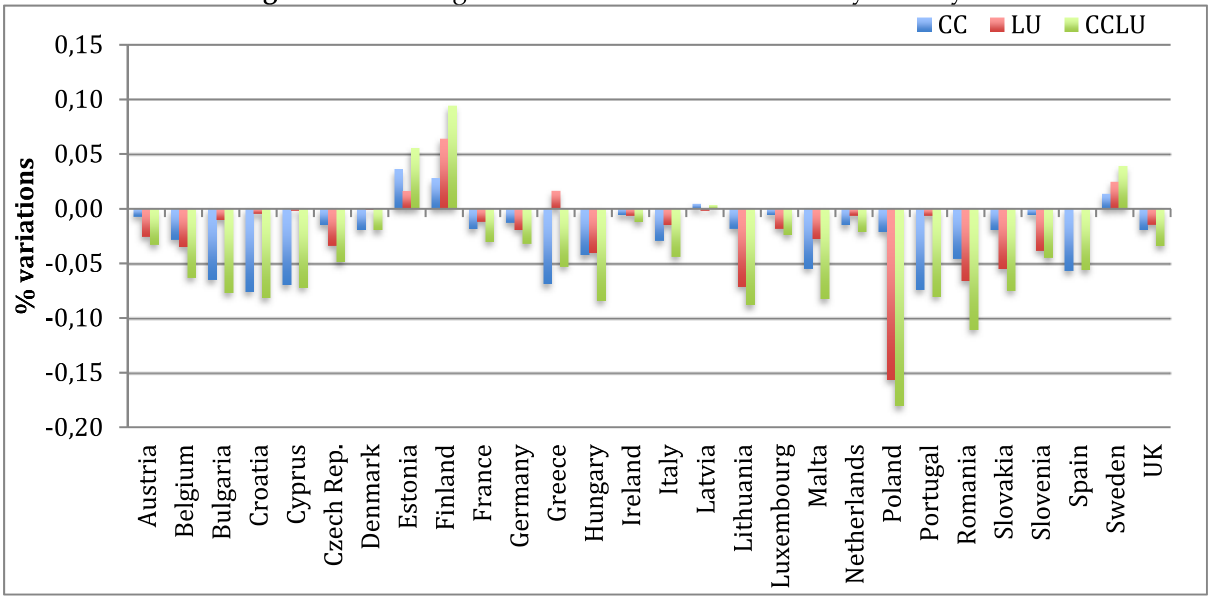
Wherever agricultural land and/or agricultural productivity are expected to decrease, so does the demand for labor (e.g., Luxembourg Belgium, Portugal, Poland, France and Malta). It is worth noting that the most negatively affected countries are those located in central-southern Europe, with some exceptions (e.g., Croatia, Cyprus, Greece).

Figure 4. Percentage variations in employment level of the overall agricultural sector.



Another relevant macroeconomic variable it is worth commenting is the national real income, a measure of household purchasing power, thereby accounting for the overall impact on welfare. Lower (higher) productivity in agriculture generates negative (positive) consequences in terms of real income and welfare, as illustrated in Figure 5.

Figure 5. Percentage variations in national income by country.



The magnitude of the loss (gain) depends on the amount of the productivity shock, but also on the share of agricultural sector in the economy. A first interesting example is Romania. This country is predicted to suffer the second largest decrease in real national income, even if the reduction in agricultural productivity and agricultural land are not among the largest. Yet, its share of agricultural activities over the total economic activity is the highest among the EU-28 countries (see Table A3 of the Appendix). A second example is Luxembourg. This country is expected to suffer from large reductions in total agricultural output and employment level. Yet, the negligible share of agriculture on its total value added (1.26%) dampens the impact on national income.

On average, the impact on the national income of the European economies is small, ranging from -0.18% predicted for Poland to 0.09% for Finland under the climate change and land-use scenario. This modest impact comes with no surprise, as the value added of agriculture represents a small fraction of total GDP in most EU economies (4.72% on average, see Table A3 of the Appendix). Most countries are negatively affected, and it is worth noting that among the largest expected impacts we find non-Mediterranean countries, like Poland, Romania, Bulgaria and Hungary, whose shares of agricultural value added are among the highest in Europe.

Changes in agricultural productivity due to climate change drive the overall results for 14 countries, especially in southern Europe. Land-use change affects more significantly the national income of central-northern economies, like Poland, Lithuania and, positively, Finland. Estonia and Sweden are also positively affected. Negligible impacts are expected in Latvia, Ireland and central Europe countries. The whole impact of climate change and land-use change (CCLU) is not just the sum of the two impacts taken alone (CC+LU), due to the many secondary-order effects at play in the structural captured by the general equilibrium adjustment process.

Another interesting question stemming from the analysis is what happens to the rest of the economy. Is it unaffected by these changes occurring in agriculture? A general economic equilibrium analysis sheds light on the extent to which other sectors are indirectly affected by the productivity shocks in agriculture, both positively and negatively. This is another consequence of the full account of changes in relative competitiveness. For example, if a negative shock affects agricultural production, it will trigger a devaluation of the currency to keep the trade balance in equilibrium. The devaluation then makes exported goods more competitive in foreign markets, thereby stimulating production in the other sectors of the economy. Table 4 presents the changes in total output for the Manufacture and Services industries. On average, Manufacture is more affected than Services by the change in relative competitiveness (e.g., Estonia, Finland, Malta, Latvia, Poland, Portugal, Spain), as Services are typically not traded internationally.

Table 4. Percentage changes in other industries' output by scenario.

Country	*CC*		*LU*		*CCLU Scenario*	
	Manuf.	*Services*	*Manuf.*	*Services*	*Manuf.*	*Services*
Austria	0.01	-0.01	0.15	0.01	0.17	0.00
Belgium	0.07	-0.02	0.31	0.06	0.38	0.04
Bulgaria	0.09	-0.04	-0.23	-0.02	-0.12	-0.06
Croatia	-0.01	-0.05	-0.11	-0.03	-0.11	-0.08
Cyprus	0.48	0.01	-0.50	-0.11	-0.02	-0.09
CzRep.	0.00	-0.02	0.17	-0.02	0.18	-0.04
Denmark	0.06	-0.01	-0.07	0.00	0.00	-0.01
Estonia	-0.29	-0.06	-0.62	-0.12	-0.95	-0.20
Finland	-0.17	0.00	-0.36	0.00	-0.55	0.00
France	0.10	0.00	0.02	0.00	0.12	-0.01
Germany	0.02	-0.01	0.18	0.01	0.20	0.00
Greece	0.16	-0.02	-0.23	-0.04	-0.07	-0.06
Hungary	0.09	-0.04	0.40	0.02	0.50	-0.02
Ireland	0.03	-0.04	-0.03	-0.04	0.01	-0.08
Italy	0.11	-0.01	0.01	-0.01	0.12	-0.02
Latvia	0.04	0.00	-0.97	-0.13	-0.89	-0.13
Lithuania	-0.05	-0.03	0.39	0.05	0.33	0.02
Luxemb.	0.00	-0.05	0.54	0.10	0.56	0.05
Malta	0.26	-0.04	0.08	-0.02	0.34	-0.06
Netherl.	0.02	-0.01	0.06	0.01	0.08	0.00
Poland	-0.02	-0.03	0.90	-0.12	0.90	-0.15
Portugal	0.48	0.00	-0.08	-0.01	0.40	-0.01
Romania	0.42	0.00	0.47	0.00	0.84	0.00
Slovakia	-0.02	-0.02	0.00	-0.07	-0.01	-0.09
Slovenia	-0.05	-0.04	0.30	0.04	0.25	0.00
Spain	0.37	0.02	-0.16	-0.03	0.21	-0.01
Sweden	-0.19	-0.04	-0.66	-0.10	-0.89	-0.14
UK	0.08	0.00	0.05	0.00	0.14	0.00

In general, where agricultural land availability or productivity is projected to increase (e.g., Greece, Latvia, Sweden), a rise in agricultural production and a reduction in the output of the other sectors are expected, with possible exceptions. In the CGE model employed in this study factors of production are fixed (their level is exogenous), fully employed and land is an imperfectly mobile factor (it can not move to non-agricultural sector). Therefore an expansion of agriculture would necessarily generate a contraction of the other sectors, as more factors (not only land) are employed in the former. On the other hand, the increase in land availability means more factor income and boosts the marginal productivity of the other production factors of the economy (capital, labor and natural resources), resulting in an increase in the output of the all sectors. Which of the two effects prevails depends on market conditions and the economic structure of the country.

3. Sensitivity analysis

To account for the high degree of uncertainty that surrounds climate change projections and its effects on agricultural productivity, this section presents a detailed sensitivity analysis that incorporates uncertainty into the model.

Indeed, the GTAP CGE model allows us to undertake 'systematic sensitivity analysis' (SSA) on key parameters and exogenous variables, using statistical quadrature techniques (Arndt, 1996). In practice, one or more parameters or shocks can be 'perturbed' on the basis of ex-ante (subjective) probability distributions; for each realization of the random variables, the model computes a general equilibrium state. Results are subsequently processed to infer the statistical distribution –the mean value and standard deviation– for all endogenous variables.

We use this methodology to account for the uncertainty surrounding the percentage variations of agricultural productivity (reported in Table 2), which represent the economic channel through which climate change affects agricultural output. These percentage variations are indeed estimated on the ground of the predicted average levels of future temperature, whose uncertainty is captured by the associated standard deviations (columns 2 and 3 in Table 1). From these, we compute the expected variations in agricultural productivity,, which are needed to study the sensitivity of results.[10]

The results from the SSA calculation are estimates of the mean value and standard deviation for each endogenous variable, from which it is possible to infer information about the likely range of variation in the variables of interest, like agricultural output and employment levels. Table 5 and 6 report the estimated variations in agricultural output and employment level, respectively, and their standard deviations.[11]

To the extent that both the variation in 2050 average temperature and its standard deviation are larger (see Table 2), the uncertainty surrounding our results is higher

[10] At present, continuous uniform and symmetric triangular are the two available distributions to carry out a SSA with RunGTAP. In the SSA undertaken in this study, we use the symmetric triangular distribution. Further information are available in Arndt and Pearson (1998).

[11] The standard deviations of the distributions for the variable "national income" computed by the SSA are very low (< 0.0001 for most countries), meaning that the uncertainty surrounding the average values reported in Figure 5 is low. For this reason, results from SSA are not reported, but are available upon request.

as well. This is the case of Finland and Sweden. All in all, the sensitivity analysis reveals that deviations around our estimates are rather small and do not change neither the sign nor (significantly) the size of our results.

Table 5. Results from sensitivity analysis: agricultural output by crop category. CCLU scenario.

5a) RICE

Countries	*% change in yield*	*St. Dev. (+/-)*	Countries	*% change in yield*	*St. Dev. (+/-)*
Austria	-5.08	0.031	**Italy**	-4.34	0.020
Belgium	-13.84	0.012	**Latvia**	-2.08	0.005
Bulgaria	-4.78	0.002	**Lithuania**	-3.25	0.006
Croatia	-3.10	0.005	**Luxemb.**	-6.13	0.004
Cyprus	-3.54	0.007	**Malta**	-1.21	0.008
CzRep.	-2.60	0.018	**Netherl.**	-5.04	0.003
Denmark	-4.37	0.006	**Poland**	-4.83	0.008
Estonia	3.40	0.004	**Portugal**	-2.35	0.004
Finland	-7.39	0.078	**Romania**	-6.33	0.016
France	-7.35	0.018	**Slovakia**	-1.90	0.019
Germany	-3.54	0.007	**Slovenia**	-1.27	0.013
Greece	-1.67	0.011	**Spain**	-5.67	0.019
Hungary	3.53	0.009	**Sweden**	-0.02	0.028
Ireland	-4.89	0.005	**UK**	-10.78	0.017

5b) WHEAT

Countries	*% change in yield*	*St. Dev. (+/-)*	Countries	*% change in yield*	*St. Dev. (+/-)*
Austria	-15.49	0.085	**Italy**	-6.08	0.043
Belgium	-13.48	0.027	**Latvia**	1.19	0.022
Bulgaria	-4.43	0.045	**Lithuania**	-15.62	0.011
Croatia	-1.78	0.009	**Luxemb.**	-38.55	0.013
Cyprus	5.99	0.020	**Malta**	-3.01	0.011
CzRep.	-6.12	0.017	**Netherl.**	-7.90	0.023
Denmark	-5.72	0.014	**Poland**	-11.42	0.006
Estonia	28.83	0.014	**Portugal**	-3.90	0.040
Finland	65.36	0.297	**Romania**	-21.72	0.031
France	-10.92	0.031	**Slovakia**	-1.58	0.034
Germany	-9.08	0.014	**Slovenia**	-6.62	0.022
Greece	4.14	0.026	**Spain**	-2.76	0.032
Hungary	-6.26	0.008	**Sweden**	20.63	0.096
Ireland	-2.14	0.018	**UK**	-7.17	0.018

(continues on next page)

Table 5 (continued)

5c) CEREALS					
Countries	*% change in yield*	*St. Dev. (+/-)*	**Countries**	*% change in yield*	*St. Dev. (+/-)*
Austria	0.88	0.001	**Italy**	0.39	0.001
Belgium	-1.12	0.001	**Latvia**	6.20	0.003
Bulgaria	0.80	0.002	**Lithuania**	-0.82	0.001
Croatia	0.46	0.001	**Luxemb.**	-11.00	0.001
Cyprus	0.53	0.002	**Malta**	-3.93	0.001
CzRep.	-1.71	0.001	**Netherl.**	0.64	0.001
Denmark	0.62	0.001	**Poland**	-2.54	0.000
Estonia	2.89	0.002	**Portugal**	-2.12	0.004
Finland	1.63	0.016	**Romania**	-2.28	0.004
France	0.42	0.001	**Slovakia**	0.24	0.003
Germany	-1.96	0.001	**Slovenia**	-1.57	0.004
Greece	0.82	0.001	**Spain**	-0.51	0.002
Hungary	-5.21	0.002	**Sweden**	4.67	0.002
Ireland	0.46	0.001	**UK**	-0.36	0.000

5d) OTHER CROPS					
Countries	*% change in yield*	*St. Dev. (+/-)*	**Countries**	*% change in yield*	*St. Dev. (+/-)*
Austria	-1.25	0.002	**Italy**	-1.85	0.004
Belgium	-3.98	0.002	**Latvia**	8.25	0.004
Bulgaria	-0.45	0.001	**Lithuania**	-0.81	0.001
Croatia	1.72	0.002	**Luxemb.**	-4.76	0.001
Cyprus	-2.81	0.003	**Malta**	-4.18	0.001
CzRep.	-1.53	0.001	**Netherl.**	-0.22	0.002
Denmark	0.96	0.004	**Poland**	-4.55	0.001
Estonia	8.13	0.005	**Portugal**	-4.32	0.006
Finland	12.15	0.040	**Romania**	-0.28	0.001
France	-0.30	0.001	**Slovakia**	0.42	0.002
Germany	-2.24	0.002	**Slovenia**	-2.83	0.001
Greece	-0.01	0.001	**Spain**	-1.93	0.006
Hungary	-1.84	0.001	**Sweden**	16.09	0.045
Ireland	0.39	0.001	**UK**	-0.98	0.001

Table 6. Results from sensitivity analysis: employment level in agricultural. CCLU scenario.

Countries	*% change in agr. employm.*	*St. Dev. (+/-)*	Countries	*% change in agr. employm.*	*St. Dev. (+/-)*
Austria	-2.78	0.14	**Italy**	-1.37	0.06
Belgium	-7.62	0.08	**Latvia**	16.35	0.05
Bulgaria	0.95	0.08	**Lithuania**	-4.02	0.03
Croatia	10.60	0.01	**Luxemb.**	-7.65	0.05
Cyprus	1.48	0.06	**Malta**	-6.18	0.03
CzRep.	1.06	0.05	**Netherl.**	0.26	0.05
Denmark	2.63	0.04	**Poland**	-4.74	0.02
Estonia	20.54	0.04	**Portugal**	-5.91	0.06
Finland	29.20	0.36	**Romania**	-2.89	0.08
France	-5.83	0.04	**Slovakia**	4.12	0.06
Germany	-2.98	0.03	**Slovenia**	-4.21	0.04
Greece	1.91	0.02	**Spain**	-0.91	0.07
Hungary	-1.51	0.03	**Sweden**	23.34	0.18
Ireland	2.59	0.04	**UK**	0.72	0.03

4. Discussion and concluding remarks

This paper provides indications of how changes in climate and land-use are expected to affect EU28 agriculture (and the whole economy) by 2050. It highlights two key results. First, climate and land-use change are likely to affect agricultural systems very differently across Europe, depending on the climate zone where countries are located. Northern countries are expected to benefit from climate change, through higher crop production, whereas other areas in Europe will suffer negative consequences in terms of reduced agricultural output, income and welfare. Rather surprisingly, Central-Eastern countries appear more vulnerable than Mediterranean ones, and will likely experience the largest drops in crop production and national income. The impact on the latter, however, is not particularly worrisome, as the share of agricultural activities over the total economic activity is small. Rather, this may change the relative future importance of Europe as a global supplier of food.

Second, land-use is likely to change in the near future, expanding suitable areas for crop cultivation and increasing agricultural production in some Northern and Southern countries. Instead, the largest drops in agricultural output due to land loss will be experienced in Eastern Europe.

These outcomes may exacerbate existing regional difference across EU28 countries, in line with recent evidence about the US, that points in the very same direction (Hsiang et al,. 2017). As argued by Olesen and Bindi (2002), adaptation strategies, like changes in crop species and sowing dates, land allocation and farming system, could effectively curb some negative effects of climate change or exploit positive effects, thus reducing regional disparities. In our simulation exercises we deliberately abstract from any adaptation/mitigation policy. In this sense, our estimates can be considered as upper and lower bounds of the potential impacts that

may be raised (if positive) or dampened (if negative) to the extent that adaptation and mitigation policies are put in place.
Improving the understanding of the potential effects of climate change on crop yields is central to design appropriate adaptation strategies, and to reform current policies in such a way to encourage a more flexible land-use and crop production. Furthermore, new developments towards less intensive farming systems, environmental protection and urbanization will also matter in shaping future agricultural systems. Understanding the combined effects of adaptation and mitigation strategies with social-economic trends therefore represents a promising topic for future research.

References

Aguiar, A., Narayanan, B. and McDougall, R. 2016. "An Overview of the GTAP 9 Data Base". *Journal of Global Economic Analysis*, 1(1): 181-208. doi: 10.21642/JGEA.010103AF.

Alcamo, J., Flörke, M., and Märker, M. 2007. "Future long-term changes in global water resources driven by socio-economic and climatic changes", *Hydrological Sciences*, 52(2): 247–275.

Alexandrov, V., Eitzinger, J., Cajic, V. and Oberforster, M. 2002. "Potential impact of climate change on selected agricultural crops in north- eastern Austria", *Global Change Biol*, 8(4): 372–389.

Arndt C. 1996. *An Introduction to Systematic Sensitivity Analysis via Gaussian Quadrature*. GTAP Technical Paper No. 2. ,

Arndt, C. and Pearson, K.R. 1998. *How to Carry Out Systematic Sensitivity Analysis via Gaussian Quadrature and GEMPACK*. GTAP Technical Paper No. 3.

Armington, P. 1969. *A theory of demand for products distinguished by place of production*. International Monetary Fund Staff Papers, XVI (1969), 159-78.

Audsley, E., Pearn, K.R., Simota, C., Cojocaru, G., Koutsidou, E., Rousevell, M.D.A., Trnka, M. and Alexandrov, V. 2006. "What can scenario modelling tell us about future European scale agricultural land use, and what not?", *Environ Sci Policy*, 9(2): 148–162.

Baranzelli, C., Jacobs-Crisioni, C., Batista, F., Castillo, C. P., Barbosa, A., Torres, J. A., and Perpiña Castillo, C. 2014. *The reference scenario in the LUISA platform—updated configuration 2014 - Towards a common baseline scenario for EC impact assessment procedures* (No. Report EUR 27019 EN). Luxembourg: Institute for Environment and Sustainability, JRC, European Commission. Retrieved from https://ec.europa.eu/jrc.

Bindi, M. and Olesen, J.E. 2011. "The responses of agriculture in Europe to climate change", *Regional Environmental Change*, 11(1): S151–S158.

Britz, W. and Witzke, P. 2008. CAPRI model documentation 2008: Version 2. *Institute for Food and Resource Economics, University of Bonn, Bonn*.

Ciscar, J.C., Iglesias, A., Feyen, L., Szabo, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O.B., Dankers, R., Garrote, L., Goodess, C.M., Hunt, A., Moreno, A., Richards, J. and Soria, A. 2011. "Physical and economic consequences of climate change in Europe", *Proc Natl Acad Sci USA*, 108(7): 2678–2683.

Cline, W.R. 2007. *Global Warming and Agriculture – Impact Estimates by Country*, Center for Global Development, Peterson Institute for International Economics, Washington D.C.

Corong E., Hertel, T.W., McDougall, R.A., Tsigas, M.E. and van der Mensbrugghe, D. 2017. "The Standard GTAP Model, Version 7", *Journal of Global Economic Analysis*, 2(1): 1-119.

Deschênes, O. and Greenstone, M. 2007. “The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather”, *Am Econ Rev*, 97(1): 354–385.

Dixon, P.B. and Jorgenson, D.W. 2013. *Handbook of Computable General Equilibrium Modeling,* vol. 1A and 1B (eds). Elsevier.

European Commission (2016). LUISA Territorial Modeling Platform. See https://ec.europa.eu/jrc/en/luisa (last accessed on May 7th, 2017)

Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J. and Leemans, R. 2005. “Future scenarios of European agricultural land use I. Estimating changes in crop productivity”, *Agric Ecosyst Environ*, 107 (2–3): 101–116.

FAO. 2007. *World agriculture: toward 2015/2030. Summary Reports*. Food and Agriculture Organization of the United Nation, Rome.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J. and Stoffel, M. 2014. “21st century climate change in the European Alps—A review”, *Science of The Total Environment*, 493: 1138–1151. doi:10.1016/j.scitotenv.2013.07.050

Greiving, S. 2011. *ESPON Climate Climate Change and Territorial Effects on Regions and Local Economies* (ESPON 2013 Programme.). Dortmund, Germany: ESPON & IRPUD.

Hermans, C. M. L., Geijzendorffer, I. R., Ewert, F., Metzger, M. J., Vereijken, P. H., Woltjer, G. B., & Verhagen, A. 2010. “Exploring the future of European crop production in a liberalised market, with specific consideration of climate change and the regional competitiveness”, *Ecological Modelling*, *221*(18): 2177–2187. doi:10.1016/j.ecolmodel.2010.03.021.

Hertel, T.W., Rosch, S., 2010. “Climate Change, Agriculture and Poverty”. *Applied Economic Perspectives and Policy*, 32(3): 355-385.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D. J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K. and Houser, T. 2017. “Estimating economic damage from climate change in the United States” *Science*, 356: 1362-1369.

García-Ruiz J.M., López-Moreno, J.I., Vicente-Serrano, S.M., Lasanta–Martínez, T. and Beguería, S. 2011. “Mediterranean water resources in a global change scenario” *Earth-Science Reviews*, 105: 121–139.

Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, J. and Martín-Carrasco, F. 2011. “Re-thinking water policy priorities in the Mediterranean region in view of climate change”, *Environmental Science and Policy*, doi: 10.1016/j.envsci.2011.02.007.

IPCC (2014), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Inter-governmental Panel on Climate Change,* Cambridge University Press.

KC, S. and Lutz, W. 2014. “The human core of the shared socioeconomic pathways: pop- ulation scenarios by age, sex and level of education for all countries to 2100”, *Global Environ. Change*, http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Kriegler, E., O’Neill, B.C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R.H. and Wilbanks, T. 2012. “The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways”, *Glob. Environ. Change*, 22: 807–22.

Kristensen, K., Schelde, K., and Olesen, J.E. 2010. “Winter wheat yield response to climate variability in Denmark”, *The Journal of Agricultural Science*, 149(1): 33-47. doi:10.1017/S0021859610000675

Jones, P.G. and Thornton, P.K. 2003. “The potential impacts of climate change on maize production in Africa and LatinAmerica in 2055”, *Global Environmental Change- Human and Policy Dimensions*, 13(1): 51–59.

Lang, G. 2007. “Where are Germany’s gains from Kyoto? Estimating the effects of global warming on agriculture”, *Clim Change*, 84(3):423–439.

Lavalle, C., Micale, F., Durrant Houston, T., Camia, A., Hiederer, R. Lazar, C., Conte, C., Amatulli, G., Genovese, G. 2010. "Climate change in Europe. 3. Impact on agriculture and forestry. A review." *Agronomy for Sustainable Development*, 29(3): 433-446.

Lobell, D.B. and Burke, M.B. 2010. "On the use of statistical models to predict crop yield responses to climate change", *Agricultural and Forest Meteorology*, 150: 1443-1452

Mendelsohn R. and Schlesinger ,M.E. 1999, "Climate Response Functions", *Ambio*, 28(4): 362-366.

Olesen, J.E. and Bindi, M. 2002. "Consequences of climate change for European agricultural productivity, land use and policy", *European Journal of Agronomy*, 16: 239–262.

Olesen, J.E., Carter, T.R., Díaz-Ambrona, C.H. Fronzek, S., Heidmann, T. Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikof, J.P., Quemada, M., Ruiz-Ramos, M., Rubæk, G.H., Sau, F., Smith B., and Sykes, M.T. 2007. "Uncertainties in projected impacts of climate change◎on European agriculture and terrestrial ecosystems based on scenarios from regional climate models", *Climatic Change*, 81:123–143.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W. 2017. "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century", *Global Environmental Change*, 42.

Richter, G.M. and Semenov, M.A. 2005. "Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks", *Agric Syst*, 84(1): 77–97.

Roson, R. and Sartori, M. 2015. "System-wide implications of changing water availability and agricultural productivity in the Mediterranean economies", *Water Economics and Policy*, 1(1): 1450001.

Roson, R. and Sartori, M. 2016. "Estimation of climate change damage functions for 140 regions in the GTAP9 database", *Journal of Global Economic Analysis*, 1(2): 78-115.

Rounsevell, M. D. A., Berry, P. M. and Harrison, P. A. 2006. "Future environmental change impacts on rural land use and biodiversity: a synthesis of the ACCELERATES project", *Environmental Science and Policy*, *9*(2): 93–100. doi:10.1016/j.envsci.2005.11.001.

Schlenker, W., Hanemann, W.M. and Fisher, A.C. 2005. "Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach", *Am Econ Rev* 95(1):395–406

Schlenker, W. and Roberts, M.J. 2009. "Nonlinear temperature effects indicate severe damages to U.S. corp yield under climate change", PNAS, 106(37): 15594-15598.

van Passel, S., Massetti, E. and Mendelsohn,. R. 2016. "A Ricardian Analysis of the Impact of Climate Change on European Agriculture", *Environ Resource Econ*, 1-36. doi:10.1007/s10640-016-0001-y.

Appendix

A1. The GTAP model

The GTAP is an international network which builds, updates and distributes a comprehensive and detailed data base of trade transactions among different industries and regions in the world, framed as a Social Accounting Matrix (SAM). The SAM is typically used to calibrate parameters for CGE models, and the GTAP data base is accompanied by a relatively standard CGE model and a package, that can be used to conduct simulation experiments (RunGTAP).

The standard GTAP model employs the simple, but robust, assumptions of constant returns to scale and perfect competition in all the markets with Walrasian adjustment to ensure a general equilibrium. Figure A1 provides a schematic representation of the GTAP modeling approach.

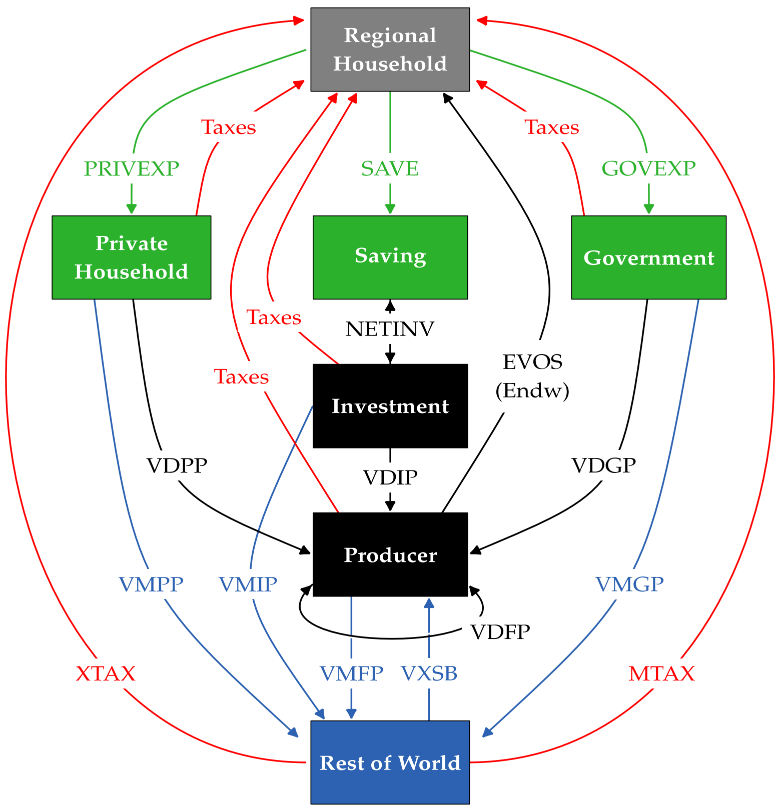


Figure A1. Circular flows in a regional economy (taken from Corong et al., 2017)

We only summarize the main relationships in the model in the following bullet points:

- a regional household collects all the income in its region and spends it over three expenditure types – private household (consumer), government, and savings, as governed by a Cobb-Douglas utility function;
- the structure of private consumption is set on the basis of utility maximization under budget constraint. The utility function is a non-

homothetic CDE function and goods have different prices and income elasticities;

- government spending is modeled by using a Cobb- Douglas sub-utility function, which maintains constant expenditure shares across all budget items;
- representative firms in each regional industry allocate factors on the basis of cost minimization. Production functions are nested CES functions, with calibrated structural parameters and given elasticities of substitution. Intermediate factors and the value added aggregate are not substitutable among themselves (Leontief). Intermediate and final demand is split according to the source of production: first between domestic production and imports, subsequently the imports among the various trading partners. The Armington assumption (Armington, 1969) is adopted: goods in the same industry but produced in different places are regarded as imperfect substitutes. Allocation is based on relative market prices, including transportation, distribution, and tax margins. Unit prices for goods and services equals average production costs, including taxes. Firms pay wages/rental rates to the regional household in return fo the employment of land, labor, capital, and natural resources. Firms sell their output to other firms (intermediate inputs), to private households, government, and investment;
- production volumes for all industries in all regions equal intermediate domestic consumption, final demand (private consumption, public consumption, demand for investment goods) and exports to all other regions;
- endowments of primary factors (e.g. labor, capital) are given and match demand from domestic industries. There is perfect domestic mobility for labor and capital (single regional price) and imperfect domestic mobility for land (industry-specific price), but no international mobility. Each sector employs two factors of production, capital and labor, with the exception of agriculture, where a third input, land, enters the production function;
- national income equals returns on primary factors owned by domestic agents, and is allocated to private consumption, public consumption and savings (constant, calibrated shares). Savings are virtually pooled by a world bank and redistributed as regional investments, on the basis of expected future returns on capital. Therefore, there is no equality between domestic savings and investment, which implies the absence of a strict trade balance constraint;
- the rest of the world gets revenues by exporting to private households, firms and government.

A2. Additional data

Table A1. Total agricultural production (M$) by crop category in EU-28 by sector in the baseline. Percentage of crop production over total agricultural production in parenthesis.

Countries	Rice	Wheat	Cereals	Other Crops	% of total EU28 agricult. production
Austria	67.53 (1%)	385.06 (8%)	757.53 (16%)	3,487.92 (75%)	1.3%
Belgium	242.07 (2%)	414.25 (4%)	193.85 (2%)	8,854.74 (91%)	2.7%
Bulgaria	161.59 (3%)	866.48 (18%)	570.73 (12%)	3,208.7 (67%)	1.3%
Croatia	301.34 (5%)	928.09 (16%)	899.22 (15%)	3,722.74 (64%)	1.6%
Cyprus	4.68 (1%)	29.43 (5%)	24.09 (4%)	507.05 (90%)	0.2%
CzechRep	42.98 (1%)	1,046.38 (19%)	768.75 (14%)	3,757.08 (67%)	1.5%
Denmark	54.73 (1%)	1,031.61 (17%)	868.35 (15%)	3,975.33 (67%)	1.6%
Estonia	4.74 (1%)	66.31 (13%)	87.29 (16%)	371.96 (70%)	0.1%
Finland	43.41 (2%)	211.66 (7%)	575.84 (20%)	2,027.27 (71%)	0.8%
France	724.4 (1%)	12,446.84 (22%)	6,904.65 (12%)	37,794.11 (65%)	16.0%
Germany	673.34 (2%)	6791.1 (15%)	3,962.93 (9%)	32,784.85 (74%)	12.2%
Greece	286.14 (2%)	638.85 (5%)	828.36 (7%)	10,080.81 (85%)	3.3%
Hungary	55.16 (1%)	1,125.39 (13%)	2,280.86 (27%)	5,032.46 (59%)	2.3%
Ireland	39.47 (1%)	190.1 (7%)	335.41 (12%)	2,236.48 (80%)	0.8%
Italy	2,003.31 (5%)	2,455.95 (6%)	3,296.71 (8%)	33,960.38 (81%)	11.5%
Latvia	8.45 (1%)	197.6 (24%)	64.97 (8%)	538.87 (67%)	0.2%
Lithuania	12.18 (0.4%)	498.53 (16%)	304.77 (10%)	2,376.87 (74%)	0.9%
Luxembourg	9.88 (2%)	17.65 (3%)	15.99 (3%)	462.77 (91%)	0.1%
Malta	1.63 (1%)	2.2 (1%)	3.76 (2%)	161.51 (96%)	0.0%
Netherlands	146.91 (1%)	300.47 (1%)	315.05 (2%)	19,680.44 (96%)	5.6%
Poland	107.84 (0.5%)	2,288.98 (10%)	3,380.66 (15%)	16,164.77 (74%)	6.1%
Portugal	319.31 (6%)	22.22 (0.4%)	228.12 (4%)	4,778.17 (89%)	1.5%
Romania	84.15 (0.3%)	1912.8 (7%)	3,899.52 (14%)	22,691.81 (79%)	7.9%
Slovakia	22.19 (2%)	343.31 (13%)	409.66 (15%)	1,910.39 (71%)	0.7%
Slovenia	28.74 (2%)	61.17 (4%)	107.83 (8%)	1,203.06 (86%)	0.4%
Spain	722.02 (2%)	1,838.03 (4%)	3,511.73 (7%)	41,127.17 (87%)	13.0%
Sweden	79.97 (2%)	514.98 (11%)	520.1 (11%)	3,727.88 (77%)	1.3%
UK	379.81 (1%)	3,451.64 (19%)	1,412.11 (8%)	12,500.4 (70%)	4.9%

Source: GTAP database

Table A2. Projected variations in GDP and population at the year 2050. SSP2.

Countries	*% change in GDP*	*% change in Pop.*	Countries	*% change in GDP*	*% change in Pop.*
Austria	70%	10%	**Italy**	97%	-11%
Belgium	156%	18%	**Latvia**	140%	42%
Bulgaria	146%	-16%	**Lithuania**	122%	2%
Croatia	194%	43%	**Luxemb.**	86%	-18%
Cyprus	123%	12%	**Malta**	205%	64%
CzRep.	44%	-4%	**Netherl.**	117%	-19%
Denmark	74%	18%	**Poland**	172%	6%
Estonia	117%	15%	**Portugal**	101%	12%
Finland	138%	-6%	**Romania**	122%	-8%
France	103%	15%	**Slovakia**	150%	6%
Germany	143%	22%	**Slovenia**	143%	-17%
Greece	158%	23%	**Spain**	139%	-2%
Hungary	127%	-1%	**Sweden**	109%	1%
Ireland	79%	-8%	**UK**	174%	33%

Source: IIASA database

Table A3. Share of agricultural value added on total GDP in the 2011 baseline.

Countries	*% share of agriculture*	*% of labor employed in agric.*	*GDP (M$US)*	*Countries*	*% share of agriculture*	*% of labor employed in agric.*	*GDP (M$US)*
Austria	1.82%	1.00%	415983	**Italy**	2.98%	2.34%	2196333.9
Belgium	1.86%	1.59%	513315.9	**Latvia**	9.20%	2.23%	28480.3
Bulgaria	6.39%	5.25%	53542.7	**Lithuania**	10.34%	8.71%	43083
Croatia	8.86%	5.08%	61520.9	**Luxemb.**	1.26%	1.03%	58009.3
Cyprus	8.06%	1.24%	24851.2	**Malta**	3.16%	2.52%	9302
CzRep.	3.76%	1.97%	216060.3	**Netherl.**	2.88%	1.71%	832751.1
Denmark	2.97%	0.86%	333742.8	**Poland**	6.03%	3.37%	515771
Estonia	4.78%	2.73%	22542.9	**Portugal**	3.13%	1.85%	237888
Finland	2.79%	0.79%	262378.3	**Romania**	16.98%	10.12%	182610.7
France	2.15%	1.81%	2777492.3	**Slovakia**	5.60%	2.74%	95877.2
Germany	1.52%	0.94%	3628098.7	**Slovenia**	5.17%	3.15%	50250.2
Greece	4.40%	6.59%	289886.2	**Spain**	3.46%	3.21%	1454530.2
Hungary	6.50%	5.00%	137451.2	**Sweden**	1.96%	0.71%	535997.4
Ireland	3.14%	1.08%	226033.6	**UK**	1.11%	0.45%	2462478.8

Source: GTAP database